Impacts on household fuel consumption from biomass stove programs in India, Nepal, and Peru

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ABSTRACT

Published data from quantitative assessments of in-home fuel use in developing countries are sparse, yet this information is important for understanding the basic daily energy consumption of half the world's population as well as the effectiveness of programs seeking to reduce the health, environmental, and socioeconomic impacts of using inefficient cooking technologies and fuels. This paper presents results from a coordinated training and field study program sponsored by the U.S. Environmental Projections Agency, with the goal of increasing our understanding of household energy use by building capacity of stove implementing organizations. The programs were conducted with stove organizations in India, Nepal, and Peru, with results from Nepal and Peru indicating the respective stove interventions resulted in significant fuel savings (~27–66%), and in India the energy consumption from combined usage of a pellet stove and liquefied petroleum gas was 59% lower than use of traditional biomass stoves. The fuel savings in Peru were highly dependent on the level of stove maintenance and user training with the largest savings (66% per capita) achieved in homes where the stoves were maintained and users were provided additional training, indicating that these are critical factors for realizing maximum stove performance in homes. Combining these results with previously published KPT results showed patterns of higher baseline fuelwood consumption in Latin America (2.1–3.4 kg per capita per day) in comparison to Nepal and India (1.0–1.4 kg per capita per day). The fuel savings estimates from the KPT studies were generally similar to savings estimates for controlled testing (Water Boiling Tests and Controlled Cooking Tests) of the respective program stoves, showing promise for better linking stove performance in the laboratory with field performance. Finally, variability of fuel consumption and fuel savings estimates are examined to inform on study design and monitoring for carbon offset methodologies.

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Introduction

The majority of households in developing countries depend on solid fuels for their primary energy use, such as cooking and heating (Rehfuess et al., 2006). Cooking with solid fuels in inefficient stoves often results in high levels of indoor air pollution (Saksena et al., 2003), which is associated with several health impacts and estimated to be responsible for 3.5 million deaths annually (Lim et al., 2012).

Solid fuel use can be costly in terms of money and time for fuel gathering/purchasing (García-Frapolli et al., 2010), and there are also considerable climate implications as inefficient cooking technologies and charcoal production produce relatively large quantities of warming species such as methane and black carbon (Johnson et al., 2008; Pennise et al., 2001; Roden et al., 2006).

Efficient stoves and fuels have been primary interventions to address these impacts, with recent interest in addressing the impacts bringing more attention and resources (Smith, 2010). The Partnership for Clean Indoor Air, for example, included over 480 Partner organizations in 2011, which sold or disseminated more than 2.5 million stoves the previous year (Colvin and Vergnano, 2011). International

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efforts such as the Global Alliance for Clean Cookstoves, as well as national stove programs in India, Peru, and Mexico, amongst others, are seeking to develop and implement more efficient cooking technologies. International carbon markets are also including more cookstove projects. Overall, this growing interest and investment in cookstoves will likely result in more scrutiny, and evaluations to verify that potential impacts are meaningful and real will be critical for justifying continued global investment in stove technologies.

Given the scope of the problem and growing global interest, there are surprisingly few current peer-reviewed estimates of fuel savings from in-home assessments (Bailis et al., 2007; Berrueta et al., 2008; Granderson et al., 2009; Wallmo and Jacobson, 1998). In turn, there is limited knowledge of how much fuel is actually being used across different regions and the overall impact stoves are producing. At a program level, organizations often rely on controlled stove testing to evaluate stove performance and lack estimates for the in-home performance of their stove(s), as in-home assessments require considerably more time and money, and can be more technically complex in terms of study design and data analysis. Using results from controlled testing to predict real stove performance, however, can be difficult as stove and fuel use practices in homes are typically much different (Bailis et al., 2007; Berrueta et al., 2008; Chen et al., 2012; Johnson et al., 2009).

In response to the need for more field-testing of stove performance, the U.S. Environmental Protection Agency (EPA) sponsored a program to assist PCIA Partner Programs in undertaking the Kitchen Performance Test (KPT), which estimates fuels consumption from daily household visits. Here we present the results from these KPTs, with fuel consumption and savings estimates from India, Nepal, and Peru.

Methods

Stove performance testing

Stove performance testing can assess a variety of metrics such as fuel efficiency, thermal efficiency, cooking time, ease of use, and emissions. Stove performance on these metrics can be applied to improve stove design and performance, inform stakeholders and potential funders, guide implementation decisions, and support the carbon credit process. The three main stove performance tests that are commonly used are the Water Boiling Test (WBT), Controlled Cooking Test (CCT), and KPT, originally developed by Volunteers in Technical Assistance (Baldwin, 1986), and later updated by the University of California, Berkeley and Aprovecho Research Center for the Shell Foundation's Household Energy and Health Program (www.pciaonline.org/testing).

- The WBT assesses stove performance using standardized cycles of boiling and simmering water under highly controlled conditions. It is generally used for stove design purposes and comparing different stoves using a common protocol.
- The CCT assesses stove performance based on preparation of common foods cooked by local people in a semi-controlled setting. CCTs are designed to compare a new or intervention stove to the stove it is primarily meant to replace while performing the same cooking task.
- The focus of this paper is the KPT, which is the least controlled and most real-world of the three tests. The KPT assesses stove performance in homes during normal daily stove use and evaluates actual impacts on household fuel consumption. It is most commonly used for program level impact evaluation.

KPT program overview

The PCIA Partners selected for this program were from a pool applications seeking to receive KPT training and assistance in carrying out the field campaign. The training and assistance was provided by Berkeley Air Monitoring Group (Berkeley, USA). The first phase of the program consisted of a training workshop at the host organization to cover the theoretical aspects of the KPT, including study design, an overview of stove performance testing, data analysis, report writing, and KPT protocols. The second phase was the field campaign, during which KPTs were conducted at the chosen study sites.

India

The Partner program in India was First Energy, who manufactures and sells the Oorja stove and the biomass pellets used in the stove. The KPT was conducted to evaluate the Oorja stove (see Fig. 1) in peri-urban neighborhoods of Kolhapur, Maharashtra. The Oorja stove is a mass-manufactured, portable, forced-air gasifier stove, optimized to use pellets made from compressed sugar cane residues.

The stove/fuel combinations in Kolhapur are varied and dynamic, with many families using a mix of fuels and stoves depending on the cooking tasks and fuel availability. The most common fuels are LPG, wood, and dung, with kerosene and pellets also used in some homes. In Kolhapur the Oorja was observed to be used in conjunction with LPG or kerosene stoves. As a transition from traditional biomass chulhas to the Oorja was not common in this area, we designed the KPT study to provide a survey of homes primarily using sugarcane pellet Oorja stoves, traditional wood-burning chulhas, and LPG stoves. This provided a cross-sectional evaluation of household energy use. Fuel consumption data were collected at the end of the rainy season (October, 2010) in 20 homes primarily using traditional wood-burning chulhas, 7 primarily using LPG, and 25 homes using both Oorjas and LPG. Oorja users were identified from a list of customers supplied by the distributors, and non-Oorja users were recruited by visiting households in the same neighborhoods.

Nepal

The Partner Programs in Nepal were the Center for Rural Technology, Nepal (CRT/N) and the Energy Sector Assistance Program (ESAP), a program executed by the Alternative Energy Promotion Center (AEPC), which hosted the KPT program. The Nepal stove assessed for this project came in two models: one-pot or two-pot, either of which could be raised or installed with the base on the ground. The stoves are built in-place, designed for wood use, constructed of mud bricks, a mixture of clay, cow dung, sugar/molasses, salt, and rice husks, reinforced with iron support rods, and with chimneys to vent smoke outside (see Fig. 1).

The study site selected for the KPT study was a series of peri-urban communities approximately 5 km east of Dhulikhel, just outside the Kathmandu Valley. Multiple cooking fuels were used in nearly all households, although wood is the dominant fuel source. Most households had small traditional charcoal stoves and an additional traditional open fire for cooking food for domestic animals. Corn cobs and bamboo were used as supplements to wood in most households. Electricity and biogas were used in some clusters, and LPG was present, but rarely used. Kerosene was used for lighting but not for cooking. The KPT was cross-sectional, performed at the end of the rainy season (late August, 2010) in 50 baseline households using traditional wood stoves and 50 households with the Improved Cooking Stove. The participants with Improved Cooking Stove had been using them for at least one year.

Peru

The Partner programs in Peru were the Servicio Nacional de Capacitación para la Industria de la Construcción (SENCICO) and the German Agency for International Cooperation's Energizing Development Program (GIZ-EnDev). The intervention stoves were two chimney stoves, the Inkawasi-UK, and the Inkawasi-Sujta. Both stoves are built in-place, have an adobe base and reinforced concrete top plate with two hot-rings for submersing pots into the combustion zone (see Fig. 1). The main difference between the stoves is that the UK

Location	Traditional stove	New/intervention stove
India	Traditional chulha	Oorja
Nepal	Traditional chulo	Nepal Improved Cooking Stove
Peru	Traditional fogón	Inkawasi

Fig. 1. Photos of typical traditional and new/intervention stoves evaluated during the KPT studies.

model has a combustion chamber made of a refractory ceramic material whereas the Sujta's combustion chamber is lined with mud bricks.

Two communities in the northern province of La Libertad were selected for the KPT study site: Santiago de Chuco and Sanagoran. Wood is the primary fuel used in this area, although some homes had LPG stoves that were rarely used. This study was designed to have cross-sectional and paired (before/after) components. The first phase of the study was a cross-sectional evaluation between the communities, with those in Santiago de Chuco using traditional stoves (N = 35) and those in Sanagoran using Inkawasis (N = 40). The second phase of the study included a paired follow-up in Santiago de Chuco (N = 13), where the Inkawasis were installed, as well as an evaluation in Sanagoran to evaluate the impact of maintenance and user training on fuel consumption. The second phase in Sanagoran was cross-sectional and included a traditional user group (N = 15), an Inkawasi group which received stove maintenance but no user training (N = 17), and an Inkawasi group which received both stove maintenance and user training (N = 20). The Inkawasi group

in the first phase in Sanagoran did not receive maintenance or training. All phases of the study were conducted during the dry season, September to December, 2010.

Kitchen Performance Test procedure

KPT protocols

For all three KPT studies, fuel consumption estimates were collected for three full days, requiring daily household visits on four days. All fuels used within each household (wood, charcoal, LPG, kerosene, pellets, dung, corn cobs, bamboo, etc.) were weighed daily using Salter Brecknell (Fairmont, MN, USA) ElectroSamson digital hand-held scales (maximum 25 kg; resolution 0.02 kg). Wood moisture was measured daily in fuelwood using households with a digital HRPQ wood moisture meter (Osprey-Talon, USA). A short survey was administered daily to record information about stove/fuel usage, the number and type of meals prepared, and the number of people for which the meals were prepared.

Table 1
Mean fuel consumption estimates for different stove/fuel user groups in India.

Stove/fuel use group	N	Standard adult/home	MJ/standard adult/day					MJ/standard adult-meal				
			Wood	LPG	Kero	Pellets	Total	Wood	LPG	Kero	Pellets	Total
Chulha	20	4.2 ± 1.3	21 ± 10	1.2 ± 3.1	0.6 ± 2.7	–	23 ± 11	6.1 ± 2.6	0.3 ± 0.8	0.2 ± 1.0	–	6.7 ± 2.7
LPG	7	4.1 ± 1.7	–	8.9 ± 4.4	–	–	8.9 ± 4.4	–	2.3 ± 1.1	–	–	2.3 ± 1.1
Oorja	25	4.4 ± 1.4	–	8.7 ± 4.4	–	2.1 ± 1.7	11 ± 5.9	–	2.9 ± 3.1	–	1.5 ± 0.8	4.4 ± 3.3

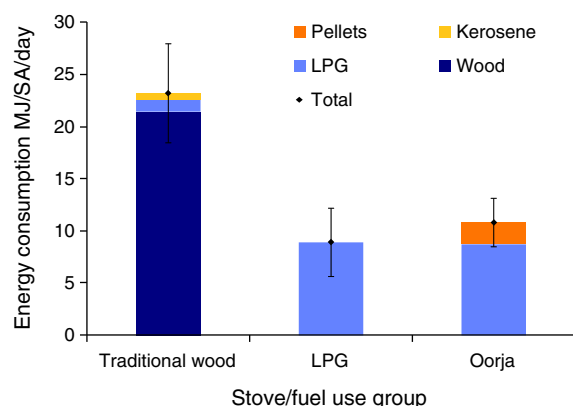Notes: Variability presented as ± 1 standard deviation.

Fig. 2. Energy consumption for stove/fuel use groups in India. Error bar represent ± 95% confidence intervals.

Fuel use and fuel savings were calculated in terms of kilograms per person per day by dividing the kilograms per household per day by the household size. The number of person-meals cooked during each day of the KPT was also determined via the daily KPT survey, and weighting factors were then applied to calculate both standard meals and standard adult equivalents (SAs). Standard meals were calculated using the following weighting factors: breakfast = 1.0, lunch = 1.0, dinner = 1.0, and tea = 0.2. Standard adult (SA) equivalents were determined using FAO standard adult weighting values: <14 years = 0.5, adult female >14 years = 0.8, adult male between 14 and 59 years = 1.0, and adult male >59 years = 0.8 (FAO, 1983). Fuel consumption data is reported per capita on a SA per day basis and per SA-meal. Energy conversions for fuels were assumed as those recommended in the KPT protocols for wood (18 MJ/kg), LPG (48 MJ/kg), and kerosene (44 MJ/kg); and 16 MJ/kg was assumed for Oorja biomass pellets (Mukunda et al., 2010).

Quality assurance and control

Quality assurance and control (QA/QC) protocols were followed across the three KPT studies to ensure that accurate and representative data was collected. Participants were instructed not to modify their typical patterns of fuel usage, fuel type, or stove use practices. Surveyors were instructed on appropriate questionnaire techniques. All scales were calibrated using NIST-traceable standardized weights. Duplicate weightings of a 10 kg reference weight were within 1%.

Duplicate wood moisture measurements had a standard deviation of 1% in Peru, 3% in India, and 4% in Nepal.

Results

India

The energy consumption estimates for each group are presented in Table 1 and Fig. 2. The fuel consumption estimates for the India study are presented based on an energy basis rather than a mass basis since the different fuel types had large differences in energy density. The energy consumption estimates are also presented without relative differences to avoid confusion that reductions in fuel consumption occurred relative to the traditional stoves, as households in the study area were generally not transitioning from traditional stoves to Oorjas.

The fuel consumption estimates indicate that homes with traditional biomass stoves required approximately double the energy for cooking compared to those using LPG and/or a combination of LPG/Oorja. Fig. 2 shows that the cooking energy consumption between exclusive LPG users and those using LPG and the Oorja was similar. Fig. 2 also shows that the Oorja was primarily a supplemental technology, as LPG cooking energy was over four times that of the Oorja on a per standard adult basis.

Nepal

Household information and fuel consumption estimates for the baseline and Improved Cooking Stove user groups are presented in Table 2 and Fig. 3. A primary consideration for comparability of groups was the use of biogas, which was common in the area. The groups were well matched, with 36% of homes in each group reporting use of biogas. There were slightly more standard adults in homes with the intervention stoves. The majority of fuel use was regular fuelwood (78–82%) with a small amount of corn cobs, bamboo, and shrubby stalks (listed as "other biomass") generally used as kindling for lighting the fire. The practice of removing pieces of charcoal from wood fires and using them later was also observed in several homes; however, as this charcoal is derived from the wood consumption, its mass is subsumed within the wood consumption estimates.

The intervention stove demonstrated significant wood savings per standard adult (30%) and per standard adult meal (26%), which are generally more robust metrics than simple consumption per household, as they control for differences in household size as well as the amount of cooking. This is especially important here given that

Table 2
Mean fuel consumption estimates for baseline and Improved Cooking Stove users in Nepal.

	N	Percent HH using biogas	SA/home	kg/standard adult/day		kg/standard adult-meal	
				Wood	Other biomass	Wood	Other biomass
Baseline	50	36%	3.5 ± 1.6	0.80 ± 0.39	0.23 ± 0.14	0.29 ± 0.15	0.08 ± 0.04
Improved Cooking Stove	50	36%	4.5 ± 2.4	0.56 ± 0.23	0.13 ± 0.12	0.21 ± 0.11	0.05 ± 0.07
Difference	–	–	**28%**	**−30%**	**−42%**	**−26%**	−34%
t-test p-value	–	–	**0.02**	**<0.01**	**0.01**	**0.01**	0.11

Notes: Variability presented as ± 1 standard deviation. Significant differences, defined as having p-values less than 0.05, are bolded. "Other biomass" refers to corn cobs, bamboo, and shrubby stalks generally used as kindling to start the fire.
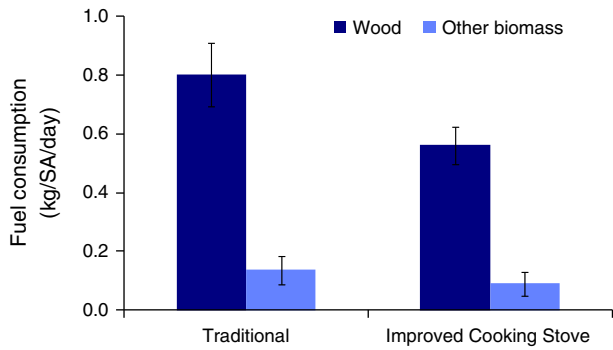
Fig. 3. Fuel consumption (kg/SA/day) comparison for traditional and Improved Cooking Stove users in Nepal. Error bars represent ±95% confidence intervals. "Other biomass" refers to corn cobs, bamboo, and shrubby stalks generally used as kindling to start the fire.

there were significantly more standard adults per home in the Improved Cooking Stove user group.

Peru

Tables 3 and 4 present household information and fuel consumption estimates for Santiago de Chuco (before/after study) and Sanagoran (cross-sectional study). Differences in standard adults per home in Santiago de Chuco were minimal as these were the same homes being sampled before and after introduction of the Inkawasi stove. The sample groups in Sanagoran were different homes, with the standard adults per home slightly higher in the Inkawasi groups with and without user training.

Tables 3 and 4 and Fig. 4 present the fuel consumption estimates for Santiago de Chuco and Sanagoran. The sample size in Santiago de Chuco was relatively small (N = 13 paired before/after homes), but the fuelwood savings from Inkawasi use were significant on per capita (38%) and per meal (31%) bases. The Santiago de Chuco participants received stove training and had well-maintained Inkawasis.

The study in Sanagoran was cross-sectional, with groups of traditional users, Inkawasi users with no training or stove maintenance, Inkawasi users who did not receive training but with a maintained stove, and users with both training and a maintained Inkawasi. The impact of training and stove maintenance appears to be strong, as users without either were not found to significantly reduce fuelwood consumption, while those with both training and maintenance demonstrated the largest savings at 66% on a per capita and per meal basis. Those with a maintained Inkawasi but no training also demonstrated significant fuel savings compared to baseline users at 50% on a per capita and per meal basis.

Fig. 4 also shows the impact of training and maintenance in Sanagoran (dark blue), with fuel consumption estimates dropping across groups with training and/or maintenance. It is also apparent that baseline fuelwood consumption was lower (Student's t-test; p < 0.01) in Santiago de Chuco, even though these communities were within ~100 km of one another, with similar climate and geographic conditions. This indicates that a cross-sectional approach between these villages would be inappropriate as the baseline fuel use is not comparable.

Table 3
Mean fuel consumption estimates for baseline and Inkawasi stove users in Santiago de Chuco.

	N	Standard Adult/home	kg/Standard Adult/day	kg/Standard Adult-meal
Baseline	13	2.9 ± 1.0	2.1 ± 0.9	0.67 ± 0.21
Maintained Inkawasi (user training)	13	2.9 ± 0.7	1.3 ± 0.7	0.46 ± 0.20
Difference	-	−3%	**−38%**	**−31%**
t-test p-value	-	0.54	**0.02**	**0.03**

Notes: Variability presented as ±1 standard deviation. Significant differences, defined as having p-values less than 0.05, are bolded.

Table 4
Mean fuel consumption estimates for baseline and Inkawasi stove users in Sanagoran.

	N	Standard Adult/home	kg/Standard Adult/day	kg/Standard Adult-meal
Baseline	15	3.3 ± 1.5	3.4 ± 1.3	1.08 ± 0.35
Inkawasi (no maintenance or training)	40	3.0 ± 1.3	2.5 ± 1.6	0.78 ± 0.51
Difference		−10%	−27%	−27%
t-test p-value		0.26	0.26	0.37
Maintained Inkawasi (no user training)	17	4.3 ± 1.6	1.7 ± 0.69	0.53 ± 0.19
Difference		32%	**−50%**	**−50%**
t-test p-value		0.06	**<0.01**	**<0.01**
Maintained Inkawasi (user training)	20	3.9 ± 1.5	1.1 ± 0.6	0.37 ± 0.15
Difference		19%	**−66%**	**−66%**
t-test p-value		0.21	**<0.01**	**<0.01**

Notes: Variability presented as ±1 standard deviation. Percentage differences are relative to the baseline scenario. Significant differences, defined as having p-values less than 0.05, are highlighted bolded in blue.

Discussion

Fuelwood consumption and savings estimates

The baseline per capita wood consumption estimates reported here fall in-line with previously reported estimates where the KPT protocol was employed and results reported in peer reviewed literature. Baseline fuelwood consumption estimates for Sanagoran and Santiago de Chuco (2.1–3.4 kg/SA/day) are similar to those from rural Michoacán, Mexico (2.3–3.4 kg/SA/day) (Berrueta et al., 2008) and Guatemala (1.9 kg/SA/day) (Boy et al., 2000); and those reported here for India (1.2 kg/SA/day) and Nepal (1.0 kg/SA/day) are also similar to previously reported estimates for India (1.2–1.4 kg/SA/day) (Bailis et al., 2007). Overall these estimates suggest differences in baseline fuel consumption between Latin America and India/Nepal. The two to three times higher baseline fuelwood consumption estimates for Latin America (2.1–3.4 kg/SA/day) compared to India/Nepal (1.0–1.4 kg/SA/day) likely arise from differences in dietary patterns, cooking practices, fuel availability, traditional stove designs, and other factors. The per capita fuel savings estimates found here are also similar for the given regions, with the Inkawasi's 27–66% savings in Peru just below that reported for the Patsari in Mexico (67%) (Berrueta et al., 2008), and the 30% savings of Nepal Improved Cooking Stove somewhat greater than those reported in India (15–19%) (Bailis et al., 2007).

The fuel savings estimates from Peru also provide compelling evidence for the importance of stove maintenance and user training. Fig. 4 shows that per capita fuel consumption dropped sequentially across Inkawasi user groups, with the largest savings (66%) achieved by those
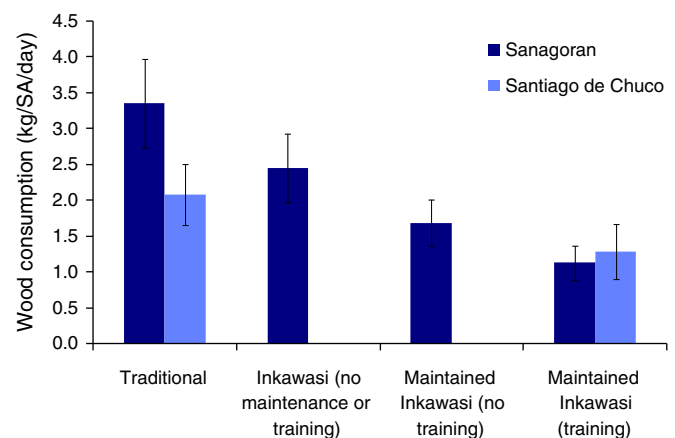

Fig. 4. Fuel consumption (kg/SA/day) comparison for traditional and Inkawasi stove users in Peru. Error bars represent ±95% confidence intervals.

who had maintained stoves and received user training within two months of the KPT data collection. This shows that maintenance and training strategies are critical components for stove programs striving to maximize in-home stove performance. These considerations may be especially important for programs which have stoves requiring sustained maintenance, such as large chimney stoves made from local materials, as well as stoves which require significant changes in user behavior to optimize fire tending and cooking practices. The frequency of training and maintenance efforts are also important considerations as stove condition and user behaviors change over time. For example, the savings for the different sample groups in the Peru program would have likely been different had the monitoring been conducted further from the training and maintenance interventions.

To our knowledge, there are few KPT-based estimates in the peer reviewed literature of stove program's impact on fuelwood consumption from other geographic areas, including Southeast Asia, China, and Africa, although a variety of different survey approaches for estimating fuel consumption have been used in these regions, or the KPT studies have been reported in gray literature or used as part of the carbon offset development process. Better regional estimates of household energy consumption would help in the development and refinement of fuel use inventories used in climate modeling, country energy balance portfolios, demand on forest and agricultural resources, and methods used for determining carbon offsets from household energy interventions.

Comparison with laboratory testing

The majority of stove testing is conducted under controlled conditions for providing rapid feedback to designers or as a standardized protocol for comparing important performance metrics across different stove technologies. Relationships between stove performance during controlled testing and during normal daily use, however, are not well understood, and recent studies have shown that prediction of stove performance in homes based on laboratory testing can be difficult (Bailis et al., 2007; Berrueta et al., 2008; Johnson et al., 2009; Roden et al., 2009). There are several factors which can contribute

to differences between laboratory and field performance. For example, WBTs are typically conducted with idealized fuel conditions and tending practices with the task of heating water, whereas cooking practices and fuel conditions in homes are highly variable and encompasse a broad spectrum of practices, many of which do not involve boiling water. CCTs incorporate local fuels and fire tending practices, but still only replicate one cooking activity. The variability and complexity of household stove and fuel use patterns also make it difficult to predict household level impacts, as multiple fuels and stoves are often employed to fulfill daily energy requirements. Furthermore, these patterns change over time due to factors such as weather, fuel availability/cost, acclimatizing to a new technology, and others (Edwards et al., 2007; Pine et al., 2011), which also limits the generalizability of results from the KPT. A recent study of a rural village in Mali, for example, tracked household energy demands over the course of a year and showed domestic energy demand approximately doubled during the short heating season (Johnson and Bryden, 2012), and studies in Mozambique and India have also shown similar patterns (Bhatt and Sachan, 2004; Brouwer and Falcão, 2004).

Fig. 5 compares the fuel savings estimates of WBTs, CCTs, and the KPTs for the stoves evaluated here. The Nepal Improved Cooking Stove demonstrated slightly higher fuel savings based on the WBT ($42 \pm 10\%$) compared to the KPT ($30 \pm 56\%$), but the CCT-based savings estimates ($28 \pm 56\%$) were within 2% of the KPT estimate. Given the difference in savings estimates for the various Inkawasi user groups in these KPTs, it is difficult to compare the laboratory and field results. For communities that have not received sufficient maintenance and training, the WBT and CCT likely overestimate fuelwood savings, but may underestimate savings in communities where stoves are well maintained and users have received sufficient training. The comparison with the Oorja is slightly different, as it presents a scenario for fuel savings given a home transitioning from traditional biomass to a combination of LPG and Oorja use. We have also included a savings estimate from a series of uncontrolled cooking tests, for which users cooked their regular meals on either a traditional biomass (wood/dung) or Oorja stove, which agrees with WBT-based savings estimates as well.
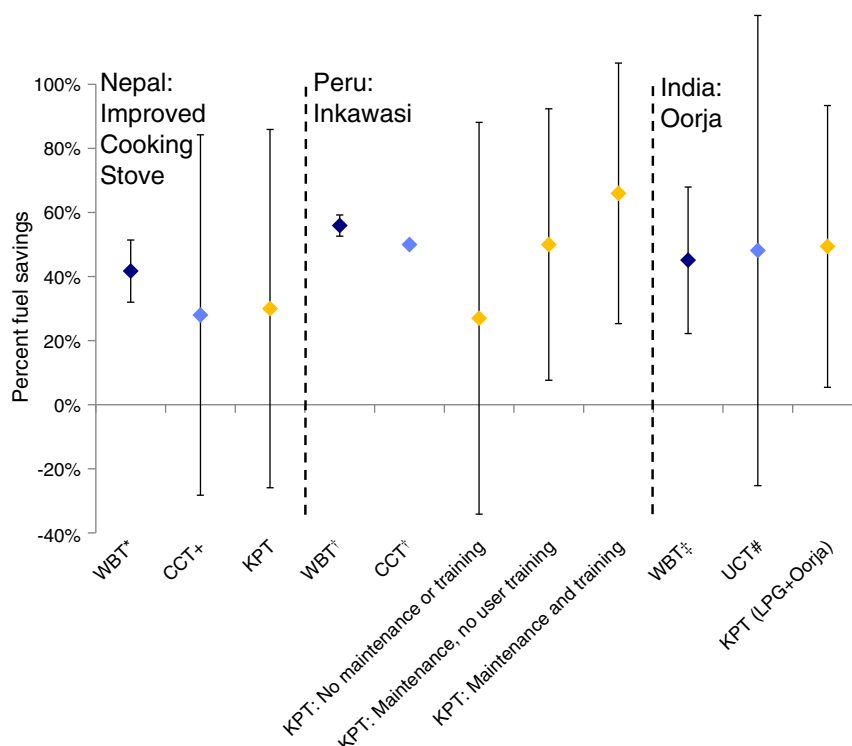

Fig. 5. Comparison of fuel savings estimates using controlled tests and KPTs. Variability is expressed as ± 1 standard deviation.

Table 5
Sample sizes required to meet precision rules of carbon offset methodologies.

Location/sample group	COV baseline	COV project	% fuel savings	COV savings	Samples sizes to meet precision rules		
					CDM: 90/10		GS: 90/30 for fuel savings
					baseline	project	
Peru: Inkawasi (no maintenance or training)	38%	63%	27%	227%	39	109	155
Peru: Maintained Inkawasi (no training)	38%	41%	50%	85%	39	46	22
Peru: Maintained Inkawasi (training)	38%	49%	66%	62%	39	66	12
Peru: maintained Inkawasi (training − Santiago de Chuco)	46%	55%	38%	119%	58	82	43
India: LPG + Oorja	47%	55%	59%	89%	60	82	24
Nepal: Improved Cooking Stove − wood	48%	41%	30%	186%	63	45	105
Mexico: Patsari wood	24%	43%	59%	50%	15	50	8
India: ARTI improved wood	45%	44%	15%	393%	56	54	465
India: DA improved wood	16%	14%	19%	104%	8	6	33
Mean	38%	45%	40%	146%	42	60	96
Median	38%	44%	38%	104%	39	54	33
Min	16%	14%	15%	50%	8	6	8
Max	48%	63%	66%	393%	63	109	465

Notes: Variability in fuel savings has been estimated by propagating the error assuming independent sample groups $\left(\sigma_{savings} = \sqrt{\sigma^2_{baseline} + \sigma^2_{project}}\right)$ with the exception of the paired Inkawasi group, for which house-by-house fuel savings estimates were available. Coefficient of variation (COV) is the ratio of the standard deviation to the mean: COV = σ/μ

The approximately 50% less energy used by the Oorja during WBTs and uncontrolled cooking tests suggests large fuel savings may be occurring in areas where homes are switching from traditional chulhas to Oorjas. Overall, these controlled tests were generally in agreement with the fuel savings from the corresponding KPTs, with the cooking-based tests showing the best agreement. This agreement shows promise for better linking laboratory and field performance, although it is difficult to know how robust these relationships are given only three sets of tests.

Fig. 5 also shows the difference in the variability of fuel savings estimates between the test types. WBTs are highly controlled, with the standard deviation of the percent fuel savings ranging from 3 to 23%, whereas uncontrolled KPTs had standard deviations of the percent fuel savings of 41–61%. The larger variation from uncontrolled testing implies that larger sample sizes are generally needed to reduce uncertainty in fuel consumption estimates for detecting statistically significant differences. A more detailed discussion on sample size is presented in the following section.

Implications for carbon offset monitoring and KPT study design

KPTs are the most time and resource intensive of standard stove performance tests, and therefore there is considerable interest in optimizing sample design. This can be especially critical for programs seeking financing through carbon credits, as in-home fuel consumption estimates are required as part of the Gold Standard methodology for voluntary emission reductions (Gold Standard, 2011) and are an option for estimating fuel consumption for the Clean Development Mechanism (CDM) methods [AMS-II.G. and AMS-I.E. (UNFCCC, 2012a,b)]. The offset methodologies provide precision rules to guide sample sizes for the required monitoring. For example, the CDM methods require that projects use either the "90/10" or "95/10" precision rule, which specifies that samples sizes for a measured parameter should be large enough that the 90% or 95% confidence interval[1] should be less than 10% of the mean, respectively.[2] Table 5 shows the hypothetical sample sizes to meet given precision rules based on the variability from published KPT studies. The CDM methods require that either the 90/10 or 95/10 rule is applied to all monitored parameters. Quantitative measurements of in-home fuel consumption are *not* required by the CDM methods,

although the KPT is an option for the baseline and project fuel consumption estimates.[3] If the KPT were to be used, the coefficients of variation[4] (COVs) for fuel consumption imply sample sizes would range from 6 to 109 to meet the 90/10 rule. The Gold Standard method requires quantitative in-home measurements of baseline *and* project fuel consumption, with the 90/30 rule applied to the fuel *savings*,[5] which have higher COVs than individual baseline or project fuel consumption estimates since savings are a function of two parameters. The hypothetical sample sizes for these KPTs to meet the Gold Standard 90/30 rule range from 8 to 465 with a median of 33. Application of precision rules to fuel savings is a more statistically sound approach than applying them separately to baseline and project fuel use estimates, as the calculations used to determine carbon offsets are largely based on fuel savings.

Overall the median samples sizes indicate that projects using the GS method should aim for sample sizes greater than 40, although careful consideration should be given to the expected fuel savings. Since fuel savings are the denominator of the precision rule equation,[6] projects with lower relative savings will generally require larger sample sizes to meet the rule and vice versa as Fig. 6 shows. For projects using the CDM methods, minimum sample sizes for meeting the 90/10 rule should be approximately 50–60.

An understanding of daily fuel consumption variability is also important for guiding study design, and future KPT efforts may benefit from further evaluation of the sampling period. The current 3-day sampling duration recommended by the KPT protocol was evaluated in the Berrueta et al. (2008) KPT study, which found that COVs dropped from 54% for one day of baseline fuel consumption estimates to 30% for three full days, with only a marginal reduction to 24% for a full week of estimates. The baseline fuel consumption estimates from this study had COVs of ~40–60%, which are well above the 30% found by Berrueta et al. (2008) for three-day KPTs. The larger variability found during these KPTs suggests that there could be considerable benefit from extending the sampling duration, although more data

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[1] Confidence intervals are a function of variability and sample size. For a normal distribution, 90% CI = $\pm 1.645 \frac{\sigma}{\sqrt{N}}$, where σ is the standard deviation, N is sample size, and 1.645 is the z-score for a 90% confidence interval.

[2] The 90/10 rule is applied if the project performs annual monitoring and the 95/10 rule is applied if the project performs monitoring every two years.

[3] There are various methods of estimating baseline fuel consumption allowed by AMS-II.G or AMS-I.E., including survey, literature, quantitative measurements, or other techniques. Fuel savings can be estimated by applying an assumed efficiency ratio of the project and traditional stove to the baseline or project fuel consumption estimate, or by measuring actual fuel consumption of the project stove in homes with a KPT.

[4] Coefficient of variation is a normalized measure of variability, defined as the ratio of the standard deviation to the mean: COV = σ/μ

[5] For Gold Standard small or micro-scale projects, the baseline fuel consumption can be estimated using the same or similar methods as those allowed by AMS-II.G or AMS-I.E.

[6] Gold Standard method precision rule: precision = (90% confidence interval)/(fuel savings)
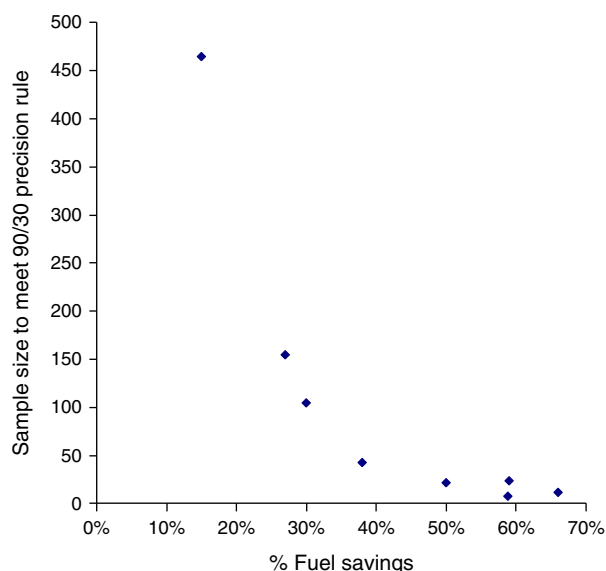
Fig. 6. Sample sizes versus fuel savings to meet Gold Standard 90/30 rule from Table 5.

would be needed to further evaluate the balance between sample duration, variability, and study cost.

Conclusions and recommendations

Conclusions

The fuel consumption estimates reported here indicate that the Nepal and Peru stove interventions produce significant fuel savings, and that the combination of Oorja/LPG usage presents an energy consumption scenario substantially lower than use of traditional biomass stoves. The fuel savings of the Inkawasi stove in Peru were highly dependent on the level of stove maintenance and user training, indicating that these are critical factors that need to be addressed for maximum stove performance to be realized. In India, the Oorja stove was used as an alternative to LPG, and thus the comparisons with traditional biomass stoves are speculative, although the fuel consumption estimates clearly suggest that there would be a considerable energy savings if traditional users were able to switch to LPG and Oorja usage.

Recommendations

• More assessments of in-home fuel consumption across a range of technologies and fuels are needed to better characterize real-world stove performance. A large-scale, global, independent field evaluation of a wide-range of stove technologies, including alternative fuels (e.g. LPG, ethanol, pellets, biogas, kerosene, plant oils), advanced stoves (e.g. forced air, gasifier, TLUD, pyrolytic), rocket stoves, and others would provide a valuable database to compare stove performance under realistic conditions. Concurrently measuring emission factors of health damaging pollutants (e.g. particulate matter and carbon monoxide) and climate forcing species (e.g. methane and black carbon) would help estimate impacts on health and climate.
• Using KPT fuel consumption estimates to map household energy demands across key geographies and demographic strata would help develop and refine fuel use inventories. Such an effort could also be used to inform on potential default, conservative baseline estimates for carbon offset methodologies.
• The KPT provides a real-world estimate for fuel consumption and savings, but is limited in time and scope. Understanding changes in fuel consumption and stove/fuel use patterns over time can also be critical for the success of a stove program, as well as for carbon offset projects. The development of protocols and monitoring technologies for tracking

stove use over time can help provide longitudinal information on the adoption and usage rates of given stove technology interventions.
• Future field assessments should be coordinated with laboratory tests to help identify key factors responsible for performance differences and develop testing/assessment approaches which better predict field performance.
• In general there is a need for increasing stove performance testing capacity for programs developing and/or disseminating household energy technologies. Efforts to increase this capacity, especially for KPTs and other in-home assessments, through workshops or training programs, such the one used to help collect the data presented here, would help address this need.

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